INVESTIGATION OF INSTABILITIES IN TWO-WAY TIME TRANSFER*

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Abstract

The U.S. Naval Observatory (USNO) and the National Institute of Standards and Technology (NIST) have begun an investigation of the instabilities in Two-Way Satellite Time and Frequency Transfer (TWSTFT). Initial results of these tests show that the time deviation (TDEV) is typically at or below 100 ps for averaging times ranging from 10 to 10^4 seconds. Beyond 10^4 seconds we see the presence of a diurnal instability that peaks at about 400 ps. The magnitude of this diurnal appears to be dependent on the earth station equipment being used and is most likely related to environmental factors. A comparison of two-way with GPS common view and GPS carrier phase is also made along with a comparative stability analysis.

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INTRODUCTION

The U.S. Naval Observatory (USNO) and the National Institute of Standards and Technology (NIST) have begun an investigation of instabilities in Two-Way Satellite Time and Frequency Transfer (TWSTFT) **[1]**. Very stable maser-based time and frequency references at USNO and NIST allow the characterization of time transfer instabilities out to about 10 days. The two-way time transfers were 2.5 Megachip per second code-based measurements and were made at Ku-band using a commercial communications satellite. The first phase of the investigation involved seven nearly continuous TWSTFT runs made between NIST in Boulder, CO and USNO in Washington, DC over the period of February to June 2002. Each run lasted 2 to 3 days and data were collected every second. These sessions provided the opportunity to characterize the stability of two-way time transfers in the range of 1 second out to about 1 day. Two different commercial two-way modems were used at both USNO and NIST and two different earth stations were used at USNO. The same earth station was used at NIST for all measurements reported here. The second phase involved TWSTFT measurements made every hour with a 13-minute duration. These measurements started on 27 June 2002 and are continuing as of January 2003. Nearly 170 days of data have been collected for analysis at the time of this writing. The same modems and earth stations were used for all of these hourly measurements. These data allow the time transfer stability to be characterized over the range of 1 hour to about 10 days. In the third phase of this project, the TWSTFT data were compared to GPS code and carrier-phase data. This allows the characterization of time transfer instabilities beyond 10 days.

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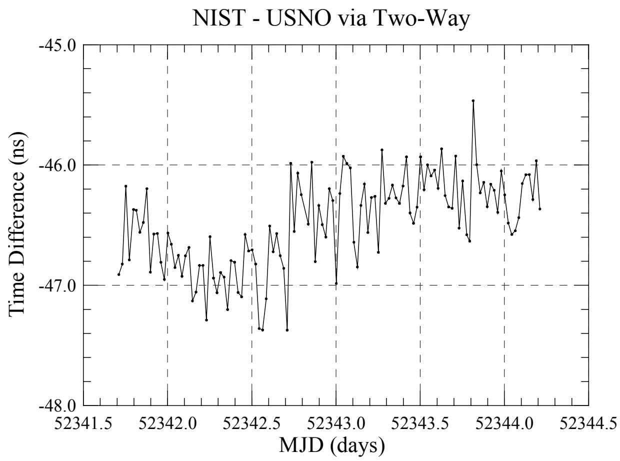

Figure 1. Time-difference data from the second continuous run.

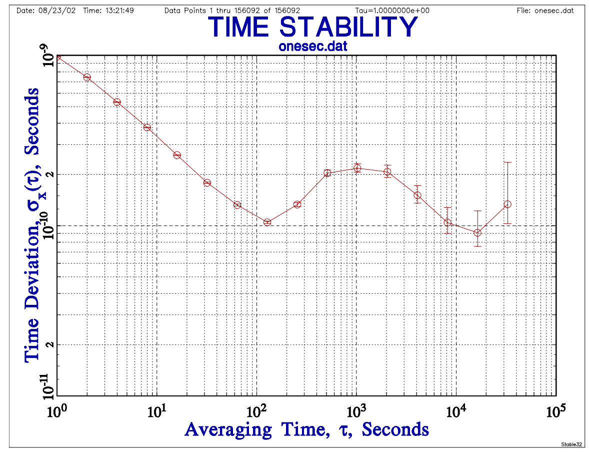

Figure 2. Time deviation from run 2.

CONTINUOUS TWO-WAY RUNS

Of the seven continuous two-way runs, only five yielded useable data. Two were devoted to working the bugs out of the system. In the second run the now discontinued MITREX **[2]** modems were used at both locations. Figure 1 shows 30-minute averages for the time-difference data. The horizontal axis is scaled in terms of the Modified Julian Date (MJD). Due to the scatter, long-term trends cannot be seen in the 1-second data, so a 30-minute average is used. The two-way link is uncalibrated, thus the absolute time difference has no significance – we were interested only in the stability of the time transfer. Figure 2 shows the results of a time-deviation (TDEV) analysis of the 1-second data. The instabilities have the characteristic of white PM noise out to about 100 seconds. Beyond 100 seconds, the noise no longer decreases and exhibits a bump around 1000 seconds that has been identified as coming from the MITREX modems. Figure 3 shows the 30-minute average time-difference data for the seventh run in which the newer SATRE **[2]** modems were used. Again, the time-difference data are uncalibrated. Figure 4 shows the TDEV results.

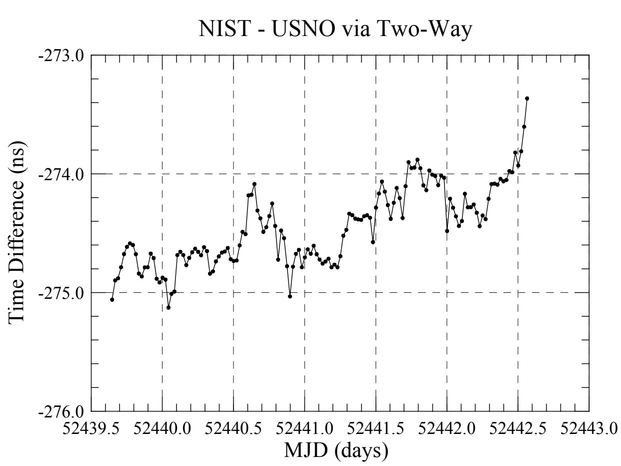

Figure 3. Time-difference data from the seventh run.

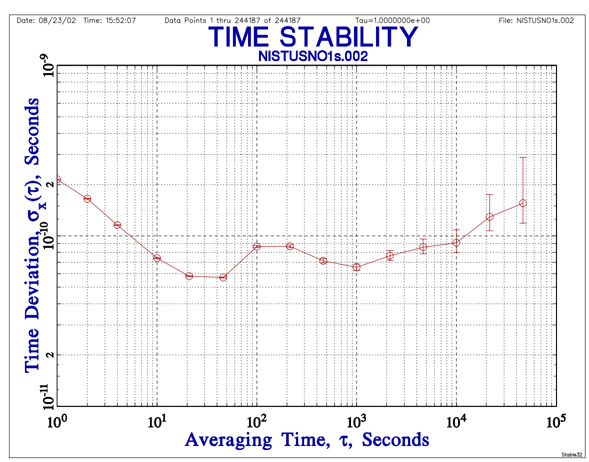

Figure 4. Time deviation from run 7.

The time-difference data in Figure 3 show less point-to-point scatter than in Figure 1, but do show more evidence of a daily (diurnal) cycle. For operational reasons, this run was made using a different earth station at USNO in which most of the electronics are located outside in a temperature environment that is uncontrolled. The earth station used at USNO for the data in Figure 1 has most of its electronics in a temperature-controlled environment. As will be discussed in the next section, we will see that the diurnal can be significantly larger than that seen in Figure 3.

In runs where the type of modems were not the same at both stations, it was necessary to offset the data collected at one site to match the time tags on the other modem. The SATRE modem averages the code frames for 1 second and, therefore, effectively moves the measurement point by 0.5 seconds relative to that in the MITREX modems. The 24-hour pattern of the satellite motion puts a diurnal time offset of a few nanoseconds peak-to-peak into the data (this is not the same diurnal as that introduced by environmental factors). When identical modems are used at both ends of the link this is not a problem.

The TDEV plot in Figure 4 shows that the white PM noise level is lower with the SATRE modems (due at least in part to the averaging), and the bump near 1000 seconds is not present. However, the time instabilities still level out a little below 100 ps. A few runs went below 50 ps in the range from 10 to 100 seconds, but all runs were back up near 100 ps by 10^4 seconds. The SATRE modems repeatedly exhibited TDEV values below 100 ps for time intervals ranging from 5 seconds to 10^4 seconds. Beyond 10^4 seconds, the diurnal begins to drive up the TDEV values.

HOURLY TWO-WAY RUNS

Figure 5 shows the uncalibrated two-way time-difference data between UTC (NIST) and UTC (USNO) for the hourly runs over a 150-day period. Each hourly session is made up of the average of 13 minutes of 1-second data. All of the data were taken with SATRE modems at both locations. About 16% of the possible data are missing due to various outages at both stations. The changes of slope in the curve are due mostly to frequency steps introduced at NIST in order to steer UTC (NIST) toward UTC. Starting at MJD 52520, the electronics package on one of the earth stations began to fail, and by MJD 52537 it was replaced. This resulted in the instabilities evident in this time interval. (Several known time steps have been removed from the data in Figure 5.) Near MJD 52595 there is a weather-related spike in the time-difference data. The other obvious feature of the data in Figure 5 is a daily fluctuation that has a magnitude of up to a few nanoseconds, and this magnitude varies from day to day. This will be discussed in more detail below.

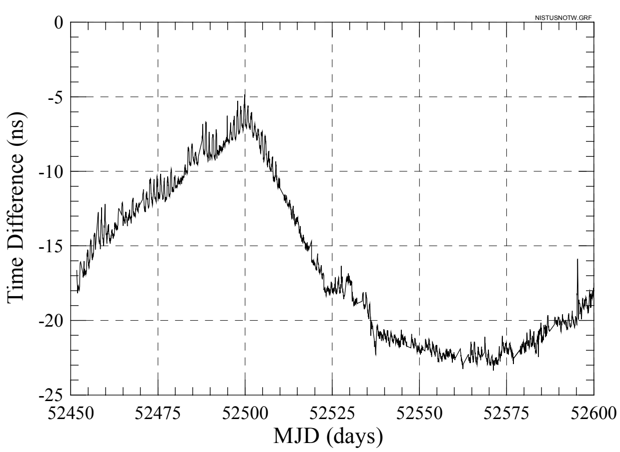

Figure 5. Uncalibrated UTC (NIST) minus UTC (USNO) for the hourly runs.

To reduce the magnitude of the slope changes due to frequency steps, we can compare the free-running (unsteered) maser-based time scales at USNO and NIST via the two-way data. These scales are the Maser Mean at USNO, and AT1 at NIST. Internal measurements (which have very low noise) are used to relate UTC (USNO) to the Maser Mean and UTC (NIST) to AT1. The results of making this transformation are shown in Figure 6. A linear slope and a fixed time offset have been removed for clarity. (There is a significant frequency offset between the two free-running scales.) The diurnal variations are more clearly evident now that the overall time-difference

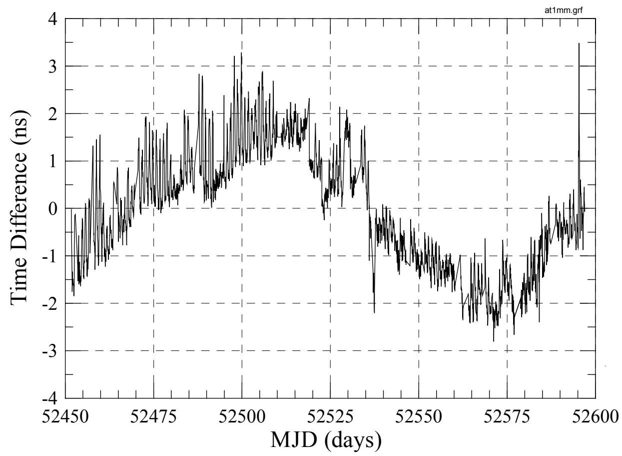

Figure 6. AT1 minus Maser Mean via two-way.

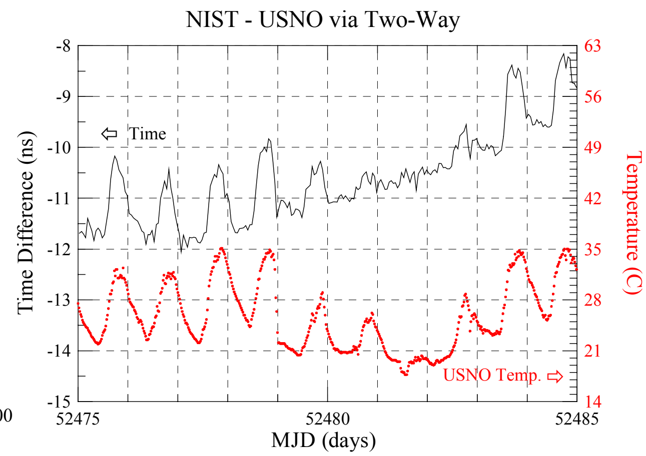

Figure 7. Correlation of diurnal with outside temperature.

excursions have been reduced. The much slower variations over the entire 150-day period are consistent with instabilities in the two free-running scales.

Figure 7 contains an expanded section of data in Figure 5 to more clearly show the diurnal time difference fluctuations. The outside temperature in the vicinity of USNO is also shown. Similar day-night temperature variations also occur in the Boulder area, but the magnitude of the fluctuations was relatively constant over this interval. This particular interval was chosen because the magnitude of the time difference diurnal exhibited significant variation, and it can be seen that this variation correlates strongly with the outside temperature in the Washington, DC area. The earth stations at both NIST and USNO contain electronics that sit outside and are exposed to environmental variations (temperature, humidity, etc.). Therefore, it is no surprise that variations in the time delay of the electronics are induced by the environment and show up in the time-difference data. Both earth stations undoubtedly contribute to the diurnal, but it appears that the station at USNO is the largest contributor. The relationship between temperature and time difference also appears to be nonlinear. An examination of all of the data shows that even though the day-night swings are of similar magnitude in both warm and cool weather, the time difference diurnal is larger when it is warm (maximum temperature goes above 30°C). It should also be pointed out that relative humidity has a strong correlation with temperature and may also play a role in the diurnal. Whatever the cause, the source needs to be identified and eliminated. A first step in this process will be either to implement temperature control of the electronics or to replace the electronics with components having low temperature coefficients.

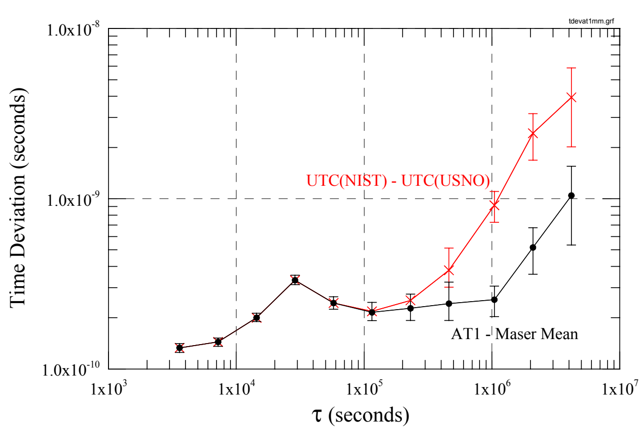

Figure 8. TDEV of data in Figures 5 and 6.

Figure 8 shows the results of a TDEV analysis of the data in Figures 5 and 6. These data complement those of Figure 4 by extending the stability analysis out to beyond 40 days. The data points below about 10^4 seconds do not match those in Figure 4 because the hourly data are not continuous (only 13 minutes each hour). Also, there are some missing data. This dead time

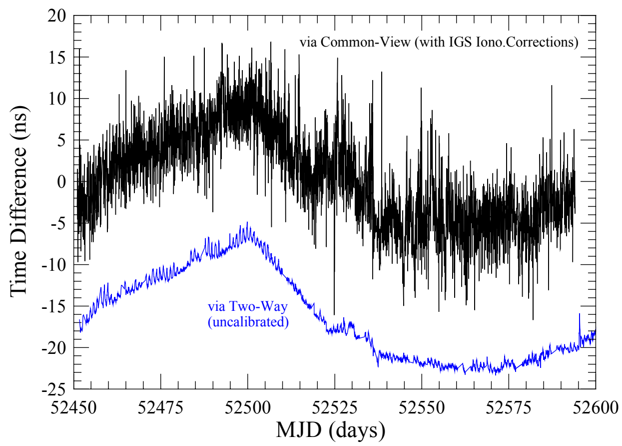

Figure 9. Comparison to GPS common view.

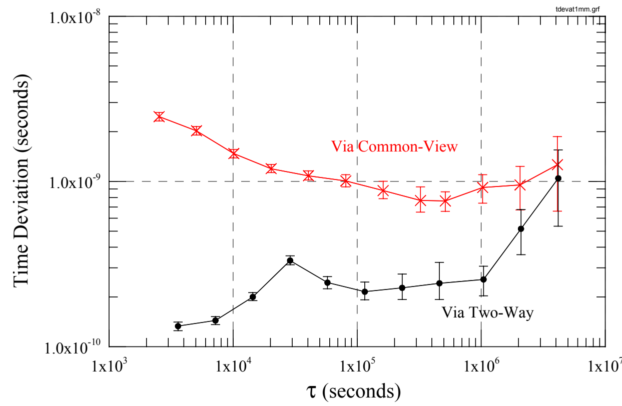

Figure 10. TDEV of data for ATI-Maser Mean as collected by common view and two-way.

results in a slightly higher TDEV for noise that is flicker in nature **[3,4]**. Between $\tau = 10^4$ and 10^5 seconds, there is a peak due to the diurnal. Finally, beyond 10^5 seconds the benefit of eliminating the frequency steps used for steering is clearly seen. For the AT1 - Maser Mean data, the TDEV values are basically flat out to about 10^6 seconds (11 days), where they then begin to increase. This increase is consistent with the stability of the timescales, but could also include some time-transfer instabilities. (The TDEVs of the maser ensembles are below 8 ps at 10^4 seconds and 20 ps at 10^5 seconds.) Thus, by using highly stable time and frequency references, we can see the time-transfer noise out to about 10 days.

COMPARISON OF TWO-WAY AND GPS COMMON VIEW

To put the two-way data into context with a well known time transfer technique, Figure 9 shows UTC (NIST) – UTC (USNO) as observed with GPS common view **[5]**. The uncalibrated two-way data are also shown for comparison. The common-view data were collected with a single-channel receiver at NIST and a multi-channel receiver at USNO. Each common-view track is 13 minutes long and there are about 34 tracks each day. As expected, the common-view data are much noisier than the two-way data. Figure 10 shows the TDEV data for AT1 – Maser Mean as observed by common view and two-way. One can see that the common-view time transfer noise dominates over virtually the entire range of analysis. The use of a multi-channel common-view receiver at both ends would increase the number of tracks by about a factor of 10 and this would improve the stability of common view for times shorter than a day. It is not clear yet that this improvement would extend much beyond 1 day.

COMPARISON OF TWO-WAY AND GPS CARRIER PHASE

Since GPS carrier-phase receivers are located at both USNO and NIST, we can also compare two-way with GPS carrier-phase time transfer **[6]**. The receiver at NIST is uncalibrated, so we cannot make calibrated time transfer measurements. Also. the NIST receiver was not made by the same manufacturer as the two at USNO. The two receivers at USNO are identified as USN1 and USN2, and the carrier-phase data are recorded at 5-minute intervals. The receiver USN1 has the same IGS designation, and is in the same building as the USNO Master Clock. However, for much of this period there were problems with the 20 MHz generator used to input frequency to the receiver. The receiver USN2 has IGS designation USNO and is located in a different building. This paper refers to it as USN2 because the data

have been re-referenced from a local clock to the USNO Master Clock. Figure 11 shows uncalibrated UTC (NIST) – UTC (USNO) via GPS carrier phase for the two USNO receivers, and also shows the two-way data for comparison. Figure 12 shows AT1 – Maser Mean with the carrier-phase data as well as the two-way data. The same slope (frequency offset) has been removed from all three curves in Fig. 12. For the sake of clarity, an arbitrary time offset has also been applied to the three curves.

It is clear from the data in Figures 11 and 12 that the short-term stability of carrier-phase time transfer is considerably better than that of two-way, and also there is no evidence of a diurnal. The data from the USN1 receiver are a little noisier than that from USN2, because its frequency reference was noisier over this period. The carrier-phase data for the two receivers show some common structure over intervals of several days that could come either from the receiver at NIST or from the carrier-phase process itself. Also, there are some differences, at similar intervals, in the data from the two receivers. In general, the carrier-phase data show more structure over periods of several days than the two-way data do. There are some gaps in the carrier-phase data, with USN1/NIST having 85% of all possible data and USN2/NIST with 70%. There were several disruptions to the receivers and associated equipment, so this is probably not the best example of carrier-phase data.

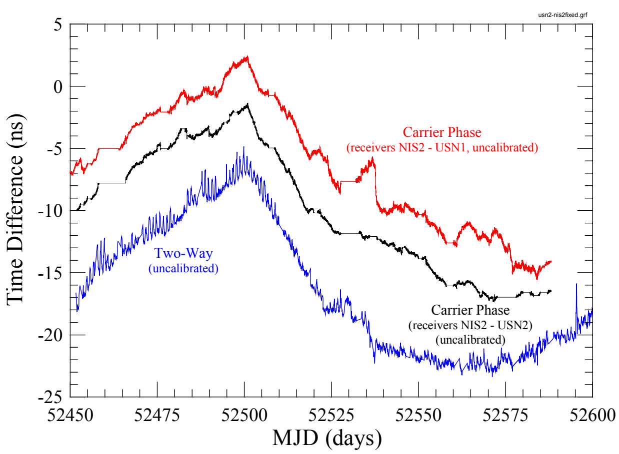

Figure 11. Uncalibrated UTC (NIST) minus UTC (USNO) via carrier phase and two-way.

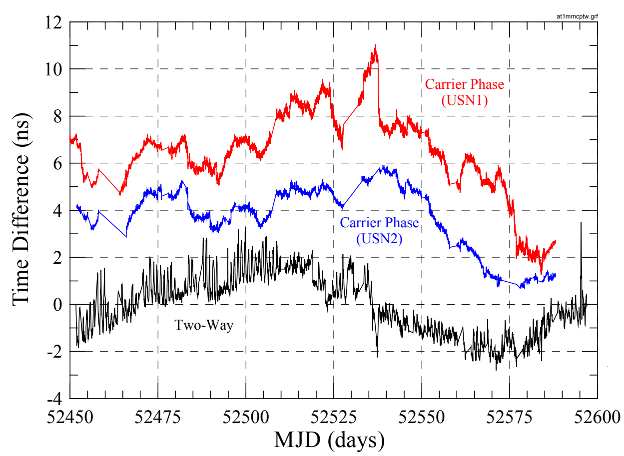

Figure 12. AT1 minus Maser Mean via carrier phase and two-way.

Figure 13 shows the TDEV of the carrier-phase data in Fig. 12. The TDEV for the two-way data is also shown for comparison. The lower noise level and the absence of a diurnal in the carrier-phase data are clearly evident in Fig. 13. As expected the noise level of USN1 is a little higher than USN2. However, the carrier-phase noise is still larger than the maser noise out to about 10^6 seconds, so we are still seeing time-transfer instabilities. Beyond 10^6 seconds we may be seeing a combination of clock and time-transfer noise.

To eliminate the clock noise from the analysis, we can difference the two-way data with the carrier-phase data. This is shown in Figure 14 for the two USNO receivers. The two curves are arbitrarily offset for clarity. We are now looking at the combined instabilities of the two time transfer techniques, since the clock noise has been removed. In the short term we see the two-way noise, but in the long term we see contributions from both two-way and carrier phase. The data in Figure 14 show that there are long-term variations on the order of plus or minus a few nanoseconds over the course of the test period. Figure 15 shows the TDEV of the two-way minus carrier-phase data. Because there are missing data in both time

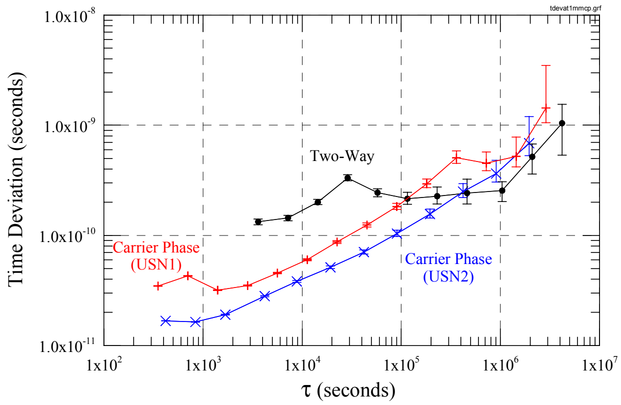

Figure 13. TDEV of AT1 minus Maser Mean for carrier phase and two-way.

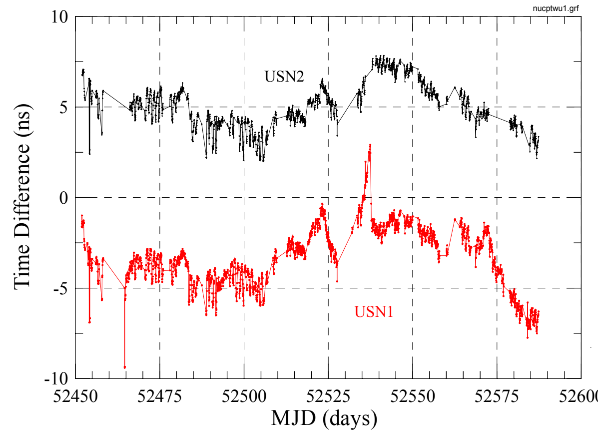

Figure 14. Two-way minus carrier phase.

transfer techniques, the data for USN1 have only 66% of the possible points and for USN2 only 55%. This complicates the calculation of TDEV, so the data in Figure 15 should be considered as only approximate. However, the general results are as expected. For values of τ less than 10^5 seconds, the two-way noise is expected to dominate, and this is what is seen, including the diurnal. Beyond 10^5 seconds, the TDEV increases and is up to about 1 ns by $3 \cdot 10^6$ seconds. This is consistent with the observed long-term instabilities in Figure 14 and is not desirable. Unfortunately, it is difficult to tell whether these instabilities come from two-way, or carrier phase, or both. One would like to see the TDEV plot stay at or below 100 or 200 ps at all times. This is an area that needs to be addressed by further investigation.

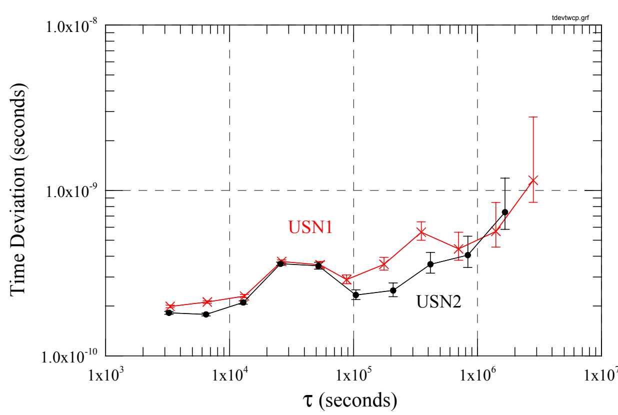

Figure 15. TDEV of two-way minus carrier phase.

SUMMARY

This investigation has provided valuable information about the stability of two-way time transfer. The continuous measurements have demonstrated that the stability of code-based two-way using modern modems is better than 100 ps for averaging times from 5 seconds to 10^4 seconds. The hourly measurements exhibited evidence of a diurnal variation in time difference that is clearly associated with earth station equipment located outside. This is an area that can be addressed with either active temperature control, or the use of equipment having very low temperature coefficients. Beyond the diurnal, the stability of the hourly measurements is in the range of 200-300 ps out to about 10^6 seconds (~11 days). Comparisons to GPS carrier phase demonstrate that carrier phase is much more stable in the short term (out to a few days). For averaging times beyond 10^6 seconds, the stability degrades, but this can be seen only by comparing two independent transfer techniques. It is not clear which technique (probably both) contributes to the long-term instabilities, and this needs further investigation.

As a result of this work, we are undertaking a number of steps to improve the stability of two-way time transfer. As mentioned earlier, improved temperature control, or lower temperature sensitivity, should help. Higher chip rates and tracking the phase of the two-way carrier should also help. Finally, the effect of the ionosphere, though small, could be reduced by two frequency measurements or using models of the ionospheric delay.

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[2] Commercial equipment has been identified because it would be impossible to duplicate the results without this information. Such identification does not imply recommendation or endorsement by the institutions involved in this study. This particular item is no longer manufactured.

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Questions and Answers

CHRISTINE HACKMAN (University of Colorado): I just wanted to ask: how did you analyze your GPS data in 24-hour batches? And, if so, how did you join the ends of those, or did you not have to do that?

TOM PARKER: Maybe I will let Demetrios answer that because he did the carrier phase. It wasn't 24-hour batches.

DEMETRIOS MATSAKIS: It wasn't 24-hour batches, indeed, and there were day-boundary jumps. They just were not visible on this scale.

HACKMAN: It seems that that could possibly add to your long-term noise.

PARKER: Correct.

MARVIN EPSTEIN (ITT Industries): Your GPS carrier-phase data – there is obviously some wander in the GPS carrier itself, because the clock wanders. How do you cancel out the actual clock wander of the GPS signal itself?

PARKER: I will let Demetrios answer that.

MATSAKIS: The ultimate time reference is the code from the GPS signal. So the carrier phase, by means of ambiguity determination, is set to the code. And to respond to Christine's comment, I don't think there will be any long-term wander from the carrier phase because it is set to the code consistently everyday. In fact, even if it were continuously filtered, there would be no long-term wander, but that is another issue.

KEN SENIOR (U.S. Naval Research Laboratory): I would concur with what Demetrios said. In fact, with respect to the day-boundary discontinuities, some recent work which was pointed out yesterday showed, in fact, that the day-boundary discontinuities are mean zero and Gaussian, and so they would not expect to introduce a walk over time.

But also, I am just curious, I recognize the USN1, which I assume is the IGS designation for the JPL real-time receiver there, but I don't recognize the USN2. Is that the USNO IGS designation for the receiver in the other building?

PARKER: Yes.

SENIOR: My point being that the USN1 receiver indeed has had a significant number of equipment changes over the year, making those data really questionable to use. But whereas, I don't think – if I am right, Demetrios – that the USN2 or the USNO receiver had any changes in equipment. Is that right?

MATSAKIS: The notations USN2 refers to data from the Ashtech Z12T receiver whose IGS designation is USNO, but with the data referenced to UTC (USNO), so that it will be common-clock with the Z12T whose IGS designation is USN1, and also the TWSTT data. We did not make any changes to the receiver USNO (USN2), but several modifications were made to the receiver USN1's setup.

HENRY FLIEGEL (The Aerospace Corporation): Could we go back to your diurnal variation chart? As you pointed out, you have a strong diurnal variation when the temperature is high, and the diurnal variation tends to vanish when the temperature is low. And, a minor comment, absolute humidity will

behave that way, too, of course. You will have a large variation in absolute humidity when the temperature is large, because then the air contains a great deal of humidity. But when the temperature is low, like 21 degrees on your chart, then, of course, there is not much absolute humidity, so the variation goes way down.

Now, I don't have a physical explanation for this because I suppose you are taking the troposphere out, so you shouldn't be affected the wet delay. But still, it might be worth remembering that maybe there is an absolute humidity effect somewhere, and indirect effect of temperature.

PARKER: You are absolutely right. It is difficult to distinguish temperature sensitivity from humidity sensitivity because the absolute moisture content tracks the temperature.

Now, in the two-way, the troposphere cancels, so it is not a propagation effect. But you can't rule out the possibility that there is something in the electronics that is sensitive to humidity. It is much more likely that it is temperature, but if you put temperature control on and it doesn't go away, then you are probably looking at humidity. That is something that has to be considered.

MATSAKIS: Let me step in here, maybe Angela McKinley or Minh Tran would like to make a comment. We've taken some of the equipment and tested it inside of an environmental chamber. And we have seen the temperature effect; I don't know if they have turned down the humidity or not. But it will be in our subsequent paper.

ANGELA McKINLEY: I was just going to say that that is Minh's paper for next year. I don't have those data. Apparently he didn't make it here today. But, yes, there is a correlation between temperature and the two-way data.

GERARD PETIT (Bureau International des Poids et Mesures): This is related to Ken Senior's comment. Is it really valid that you have so many disruptions in the carrier-phase equipment? This is not my experience in this kind of equipment.

PARKER: Demetrios might want to answer that.

MATSAKIS: The problem was probably not in the Z12T. It was probably in the converter turning 5 megahertz into 20 megahertz. And we think we have fixed it now.